Supplementary Information

Tree height and leaf drought tolerance traits shape growth responses across droughts in a temperate broadleaf forest

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Table S1. Monthly Palmer Drought Severity Index (PDSI), and its rank among all years between 1950 and 2009 (driest=1), for focal droughts.

year	month	PDSI	rank
1966	May	-2.98	2
	June	-3.40	2
	July	-4.08	2
	August	-4.82	1
1977	May	-2.96	3
	June	-3.28	3
	July	-3.61	3
	August	-3.68	3
1999	May	-3.63	1
	June	-4.21	1
	July	-4.53	1
	August	-4.64	2

Table S2. Species-specific regression equations for bark thickness (mm) as a function of diameter at breast height without bark (mm).

Species	Equations	R^2
Carya cordiformis	$ln[r_{bark}] = -1.56 + 0.416 * ln[DBH]$	0.226
Carya glabra	$ln[r_{bark}] = -0.393 + 0.268 * ln[DBH]$	0.04
Carya ovalis	$ln[r_{bark}] = -2.18 + 0.651 * ln[DBH]$	0.389
Carya tomentosa	$ln[r_{bark}] = -0.477 + 0.301 * ln[DBH]$	0.297
Fagus grandifolia	-	-
Fraxinus americana	$ln[r_{bark}] = 0.418 + 0.268 * ln[DBH]$	0.256
Juglans nigra	$ln[r_{bark}] = 0.346 + 0.279 * ln[DBH]$	0.246
Liriodendron tulipifera	$ln[r_{bark}] = -1.14 + 0.463 * ln[DBH]$	0.545
Quercus alba	$ln[r_{bark}] = -2.09 + 0.637 * ln[DBH]$	0.603
Quercus prinus	$ln[r_{bark}] = -1.31 + 0.528 * ln[DBH]$	0.577
Quercus rubra	$ln[r_{bark}] = -0.593 + 0.292 * ln[DBH]$	0.101
Quercus velutina	$ln[r_{bark}] = 0.245 + 0.219 * ln[DBH]$	0.087

We used linear regression on log-transformed data to relate r_{bark} to the diameter inside bark from 2008 data. These were then used to determine r_{bark} in the DBH_Y reconstruction (DBH in year Y). No bark correction was applied for *Fagus grandifolia*, which has thin bark.

Table S3. Species-specific regression equations for height (m) as a function of DBH (cm)

Species	Equations	R^2
Carya cordiformis	ln[H] = 0.332+0.808*ln[DBH]	0.874
Carya glabra	ln[H] = 0.685+0.691*ln[DBH]	0.841
Carya ovalis	ln[H] = 0.533+0.741*ln[DBH]	0.924
Carya tomentosa	ln[H] = 0.726+0.713*ln[DBH]	0.897
Fagus grandifolia	ln[H] = 0.708+0.662*ln[DBH]	0.857
Liriodendron tulipifera	ln[H] = 1.33+0.52*ln[DBH]	0.771
Quercus alba	ln[H] = 0.74+0.645*ln[DBH]	0.719
Quercus prinus	ln[H] = 0.41+0.757*ln[DBH]	0.886
Quercus rubra	ln[H] = 1.00+0.574*ln[DBH]	0.755
all	ln[H] = 0.839+0.642*ln[DBH]	0.857

Table S4. Individual tests of species traits as drivers of drought resistance, where Rt is used as the response variable.

		all droughts		1966		1977		1999	
variable	category	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients
xylem porosity	R	-0.8	0.0630	2.29**	0.190	1.92	-0.152	3.36**	0.1500
	D/SR		0.0000		0.000		0.000		0.0000
PLA		6.7**	-0.0140	9.13**	-0.025	-0.32	-0.010	-0.95	-0.0070
LMA		-2.01	0.0002	-1.9	0.001	-1.68	-0.002	-2.03	0.0003
π_{tlp}		1.33	-0.1740	-1.65	-0.107	1.23	-0.245	-0.1	-0.1690
WD		-1.97	-0.0310	-1.26	-0.206	-1.44	-0.154	0.66	0.2720

Variable abbreviations are as in Table 2. ΔAICc is the AICc of a model excluding the trait minus that of the model including it.

**ΔAICc > 2: variable considered significant as an individual predictor

Table S5. Individual tests of species traits as drivers of drought resistance, where Rt_{ARIMA} is used as the response variable.

		all droughts		1966		1977		1999	
variable	category	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients
xylem porosity	R	-1.47	0.0420	0.95	0.1520	2.84**	-0.171	2.27**	0.155
	D/SR		0.0000		0.0000		0.000		0.000
PLA		4.48**	-0.0120	10.15**	-0.0240	-0.9	-0.008	-1.67	-0.005
LMA		-1.99	-0.0003	-2.02	0.0005	-0.42	-0.003	-1.9	0.001
π_{tlp}		0.42	-0.1510	-1.94	-0.0530	-0.53	-0.179	0.04	-0.200
WD		-1.94	-0.0390	-0.08	-0.3040	-1.57	-0.142	0.83	0.316

Variable abbreviations are as in Table 2. ΔAICc is the AICc of a model excluding the trait minus that of the model including it.

**ΔAICc $>$ 2: variable considered significant as an individual predictor

Table S6. Individual tests of species traits as drivers of drought recovery (Rc).

		all droughts		1966		1977		1999	
variable	category	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients
xylem porosity	R	15.25**	-0.280	9.9**	-0.474	-1.67	-0.0370	17.06**	-0.3380
	D/SR		0.000		0.000		0.0000		0.0000
PLA		-1.98	0.002	-1.33	0.014	1.10	-0.0090	-2.03	0.0010
LMA		-1.35	-0.002	0.32	-0.008	-2.04	-0.0001	-2.03	-0.0005
π_{tlp}		-1.13	-0.149	-1.94	-0.101	1.08	-0.1630	-1.14	-0.2020
WD		-1.86	-0.088	-1.6	0.278	-1.68	-0.0980	-1.03	-0.2950

Variable abbreviations are as in Table 2. ΔAICc is the AICc of a model excluding the trait minus that of the model including it.

**ΔAICc > 2: variable considered significant as an individual predictor

Table S7. Individual tests of species traits as drivers of drought resilience (Rs).

		all droughts		1966		1977		1999	
variable	category	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients	ΔAICc	coefficients
xylem porosity	R	0.24	-0.147	-1.29	-0.110	1.42	-0.263	-1.11	-0.0840
	D/SR		0.000		0.000		0.000		0.0000
PLA		1.09	-0.016	1.09	-0.020	-0.51	-0.017	0.67	-0.0130
LMA		-1.9	-0.001	-1.00	-0.004	-1.95	-0.001	-2.02	-0.0004
π_{tlp}		2.5**	-0.347	-1.11	-0.212	1.57	-0.468	6.11**	-0.3730
WD		-1.83	-0.109	-2.05	-0.020	-1.37	-0.298	-2.02	0.0360

Variable abbreviations are as in Table 2. ΔAICc is the AICc of a model excluding the trait minus that of the model including it.

**ΔAICc $>$ 2: variable considered significant as an individual predictor

Table S8. Summary of top full models for each drought instance, where Rt is used as the response variable.

drought	ΔAICc	$Marginal R^2$	$Conditional R^2$	Intercept	$ln[H]$	$ln[TWI]$	$ln[H] * ln[TWI]$	PLA	π_{tlp}
all	**0.000**	**0.08**	**0.12**	**1.131**	**-0.057**	**-0.086**	**-**	**-0.012**	**-0.113**
	0.583	0.06	0.11	1.423	-0.055	-0.086	-	-0.013	-
	0.726	0.08	0.12	1.537	-0.202	-0.326	0.082	-0.012	-0.114
	1.352	0.06	0.11	1.826	-0.198	-0.324	0.081	-0.013	-
1966	**0.000**	**0.16**	**0.25**	**1.622**	**-0.135**	**-**	**-**	**-0.025**	**-**
1977	**0.000**	**0.06**	**0.22**	**0.503**	**-**	**-0.144**	**-**	**-**	**-0.24**
	0.908	0.01	0.21	1.069	-	-0.144	-	-	-
	0.988	0.06	0.22	0.568	-0.03	-0.139	-	-	-0.246
	1.144	0.08	0.24	0.684	-	-0.142	-	-0.007	-0.204
	1.267	0.04	0.22	1.211	-	-0.141	-	-0.01	-
1999	**0.000**	**0.01**	**0.18**	**1.061**	**-**	**-0.102**	**-**	**-**	**-**
	0.023	0.04	0.19	0.659	-	-0.101	-	-	-0.169
	0.954	0.02	0.19	1.157	-	-0.1	-	-0.007	-
	1.513	0.05	0.21	0.783	-	-0.1	-	-0.005	-0.145
	1.803	0.01	0.18	1.024	0.013	-0.103	-	-	-
	1.901	0.04	0.19	0.635	0.011	-0.102	-	-	-0.166

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 (ΔAICc<1) of the best model (bold). R^2 refers to conditional R^2. Year was included in the model for all drought years and appeared in all its top models, but coefficients were small (1966: 0, 1977: -0.019, 1999: -0.005; same values in all top models).

Table S9. Summary of top models for each drought instance, where Rt_{ARIMA} is used as the response variable.

drought	ΔAICc	$Marginal R^2$	$Conditional R^2$	Intercept	$ln[H]$	$ln[TWI]$	$ln[H] * ln[TWI]$	PLA	π_{tlp}
all	**0.000**	**0.05**	**0.09**	**2.113**	**-0.307**	**-0.506**	**0.14**	**-0.012**	**-**
	0.419	0.06	0.10	1.872	-0.31	-0.508	0.141	-0.011	-0.096
	1.217	0.05	0.09	1.395	-0.06	-0.1	-	-0.012	-
	1.698	0.06	0.10	1.153	-0.062	-0.1	-	-0.011	-0.095
1966	**0.000**	**0.17**	**0.23**	**1.660**	**-0.154**	**-**	**-**	**-0.024**	**-**
	1.393	0.17	0.23	1.735	-0.152	-0.047	-	-0.024	-
	1.457	0.16	0.23	1.859	-0.152	-	-	-0.025	0.078
1977	**0.000**	**0.01**	**0.16**	**1.130**	**-**	**-0.18**	**-**	**-**	**-**
	0.424	0.02	0.16	2.453	-0.461	-0.896	0.25	-	-
	0.688	0.03	0.17	0.720	-	-0.179	-	-	-0.173
	0.922	0.04	0.17	2.040	-0.466	-0.898	0.251	-	-0.18
	0.927	0.03	0.17	1.248	-	-0.177	-	-0.008	-
	1.322	0.03	0.17	2.569	-0.461	-0.893	0.25	-0.008	-
	1.709	0.01	0.15	1.183	-0.02	-0.177	-	-	-
1999	**0.000**	**0.04**	**0.20**	**0.563**	**-**	**-0.076**	**-**	**-**	**-0.2**
	0.064	0.03	0.19	0.421	-	-	-	-	-0.202
	0.127	0.00	0.18	1.036	-	-0.077	-	-	-
	0.256	0.00	0.18	0.899	-	-	-	-	-
	1.777	0.04	0.20	0.529	0.016	-0.078	-	-	-0.195
	1.797	0.01	0.20	1.101	-	-0.076	-	-0.004	-
	1.815	0.00	0.18	0.986	0.018	-0.079	-	-	-
	1.838	0.01	0.20	0.972	-	-	-	-0.005	-
	1.933	0.03	0.19	0.391	0.012	-	-	-	-0.199
	1.979	0.04	0.21	0.612	-	-0.075	-	-0.002	-0.19
	1.999	0.04	0.21	0.482	-	-	-	-0.002	-0.19

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 (ΔAICc<1) of the best model (bold). R^2 refers to conditional R^2. Year was included in the model for all drought years and appeared in all its top models, but coefficients were small (1966: 0, 1977: -0.03, 1999: 0.008; same values in all top models).

Table S10. Summary of top models for each drought instance, where Rc is used as the response variable.

drought	ΔAICc	$Marginal R^2$	$Conditional R^2$	Intercept	$ln[H]$	$ln[TWI]$	$ln[H] * ln[TWI]$	PLA	π_{tlp}
all	**0.000**	**0.05**	**0.17**	**0.434**	**0.345**	**0.844**	**-0.269**	**-**	**-**
	0.995	0.05	0.17	1.913	-0.126	-	-	-	-
	1.135	0.06	0.17	0.077	0.344	0.845	-0.269	-	-0.152
	1.991	0.05	0.18	0.410	0.346	0.843	-0.269	0.002	-
1966	**0.000**	**0.01**	**0.28**	**-0.797**	**0.89**	**1.263**	**-0.475**	**-**	**-**
	1.040	0.00	0.25	1.577	-	-	-	-	-
	1.367	0.02	0.30	-0.984	0.888	1.257	-0.474	0.013	-
	1.785	0.00	0.26	1.781	-	-0.114	-	-	-
	1.956	0.01	0.30	-1.025	0.89	1.261	-0.475	-	-0.097
1977	**0.000**	**0.17**	**0.17**	**2.485**	**-0.482**	**-**	**-**	**-**	**-0.157**
	0.299	0.17	0.17	2.943	-0.47	-	-	-0.008	-
	0.716	0.17	0.18	2.657	-0.477	-	-	-0.006	-0.114
	0.807	0.17	0.18	1.152	0.071	1.026	-0.308	-0.009	-
	0.875	0.17	0.18	2.729	-0.47	0.124	-	-0.009	-
	0.891	0.17	0.18	2.271	-0.479	0.115	-	-	-0.158
	0.910	0.17	0.18	0.712	0.054	1.004	-0.304	-	-0.159
	1.315	0.17	0.18	0.871	0.065	1.023	-0.308	-0.006	-0.112
	1.331	0.16	0.17	2.805	-0.464	-	-	-	-
	1.372	0.17	0.18	2.445	-0.475	0.122	-	-0.006	-0.112
	1.974	0.16	0.17	2.597	-0.466	0.118	-	-	-
1999	**0.000**	**0.00**	**0.16**	**1.281**	**-**	**-**	**-**	**-**	**-**
	0.532	0.00	0.17	1.093	-	0.105	-	-	-
	1.091	0.02	0.19	0.779	-	-	-	-	-0.212
	1.609	0.02	0.19	0.578	-	0.106	-	-	-0.217
	1.755	0.00	0.17	1.200	0.027	-	-	-	-
	1.996	0.00	0.18	1.251	-	-	-	0.002	-

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 (ΔAICc<1) of the best model (bold). R^2 refers to conditional R^2. Year was included in the model for all drought years and appeared in all its top models (1966: 0, 1977: -0.14, 1999: -0.217; same values in all top models).

Table S11. Summary of top models for each drought instance, where Rs is used as the response variable.

drought	ΔAICc	$Marginal R^2$	$Conditional R^2$	Intercept	$ln[H]$	$ln[TWI]$	$ln[H] * ln[TWI]$	PLA	π_{tlp}
all	**0.000**	**0.10**	**0.17**	**-0.265**	**0.348**	**0.864**	**-0.291**	**-0.012**	**-0.287**
	0.176	0.08	0.16	-0.572	0.347	0.859	-0.291	-	-0.347
	1.518	0.07	0.16	0.458	0.354	0.866	-0.292	-0.016	-
	1.552	0.09	0.17	1.253	-0.166	-	-	-0.011	-0.288
	1.698	0.08	0.16	0.940	-0.166	-	-	-	-0.348
1966	**0.000**	**0.04**	**0.15**	**1.834**	**-0.085**	**-**	**-**	**-0.02**	**-**
	0.402	0.03	0.16	1.589	-	-	-	-0.02	-
	1.189	0.00	0.14	1.534	-0.082	-	-	-	-
	1.313	0.00	0.15	1.293	-	-	-	-	-
	1.692	0.04	0.16	1.534	-0.085	-	-	-0.018	-0.116
1977	**0.000**	**0.14**	**0.28**	**-0.932**	**0.294**	**1.207**	**-0.384**	**-**	**-0.467**
	0.497	0.13	0.28	1.194	-0.383	-	-	-	-0.469
	1.304	0.15	0.30	-0.648	0.294	1.208	-0.383	-0.011	-0.411
	1.542	0.13	0.28	1.026	-0.387	0.095	-	-	-0.472
	1.555	0.09	0.28	0.138	0.304	1.211	-0.385	-	-
	1.852	0.14	0.29	1.467	-0.381	-	-	-0.01	-0.416
1999	**0.000**	**0.07**	**0.13**	**0.237**	**-**	**-**	**-**	**-**	**-0.366**
	0.313	0.08	0.14	0.472	-	-	-	-0.008	-0.317
	0.503	0.07	0.13	0.358	-0.048	-	-	-	-0.376
	0.532	0.07	0.13	0.394	-	-0.086	-	-	-0.364
	0.726	0.09	0.14	0.588	-0.047	-	-	-0.008	-0.328
	1.079	0.09	0.15	0.602	-	-0.081	-	-0.008	-0.319
	1.249	0.07	0.13	0.495	-0.044	-0.08	-	-	-0.374
	1.706	0.09	0.14	0.699	-0.044	-0.075	-	-0.007	-0.329

Models are ranked by AICc. Shown are all models whose AICc value falls within 2.0 (ΔAICc<1) of the best model (bold). R^2 refers to conditional R^2. Year was included in the model for all drought years and appeared in all its top models (1966: 0, 1977: -0.099, -0.099, -0.099, -0.097, -0.097; 1999: -0.174, -0.174, -0.174, -0.173, -0.172).

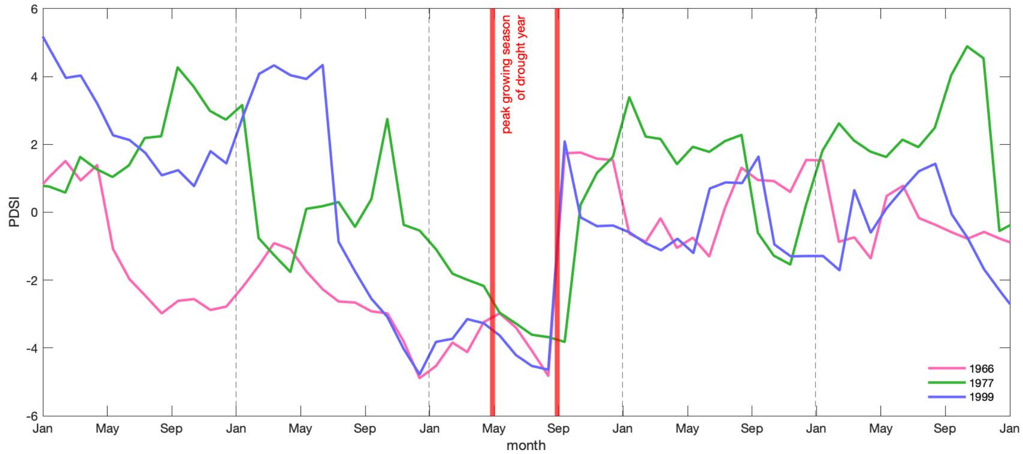

Figure S1. Time series of Palmer Drought Severity Index (PDSI) for each focal drought year ± 2 years

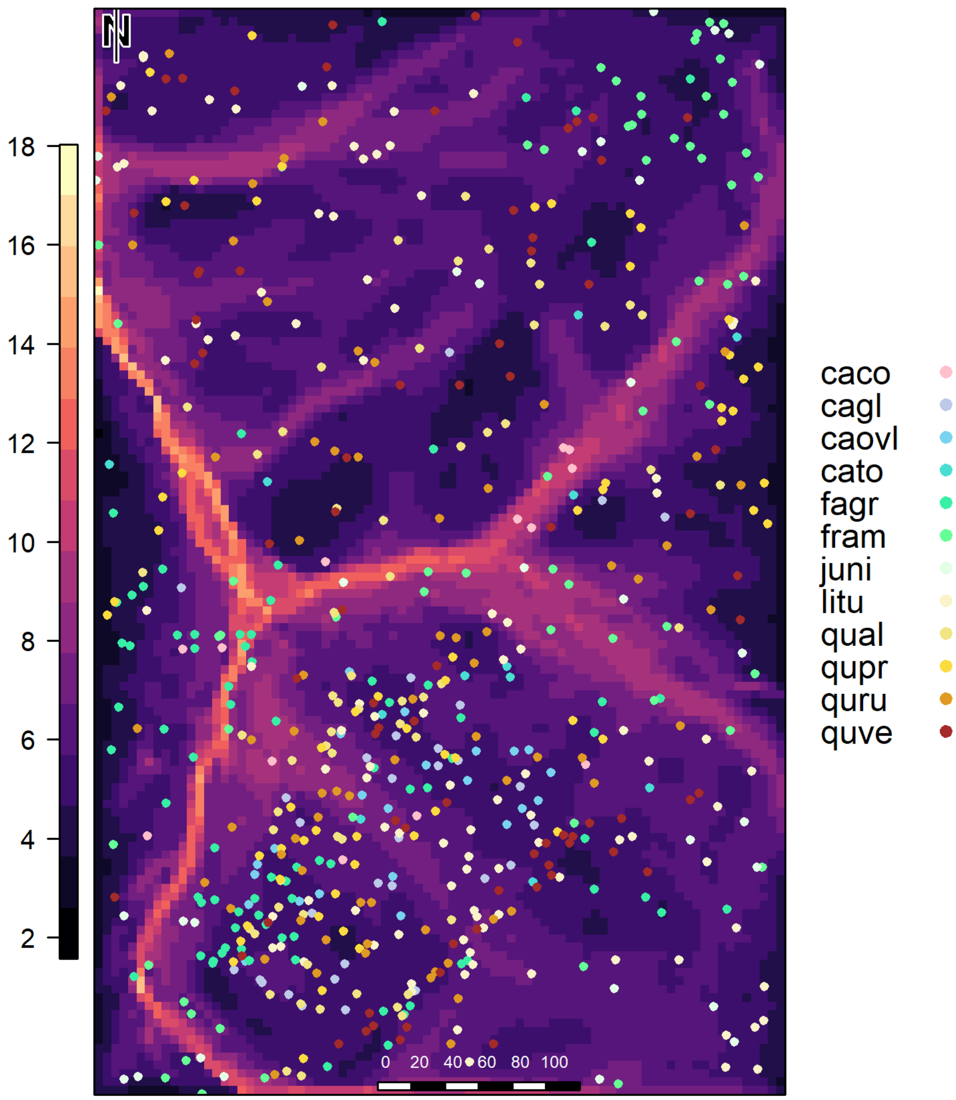

Figure S2. Map of ForestGEO plot showing topographic wetness index (color scale) and location of cored trees. Scale units are in meters

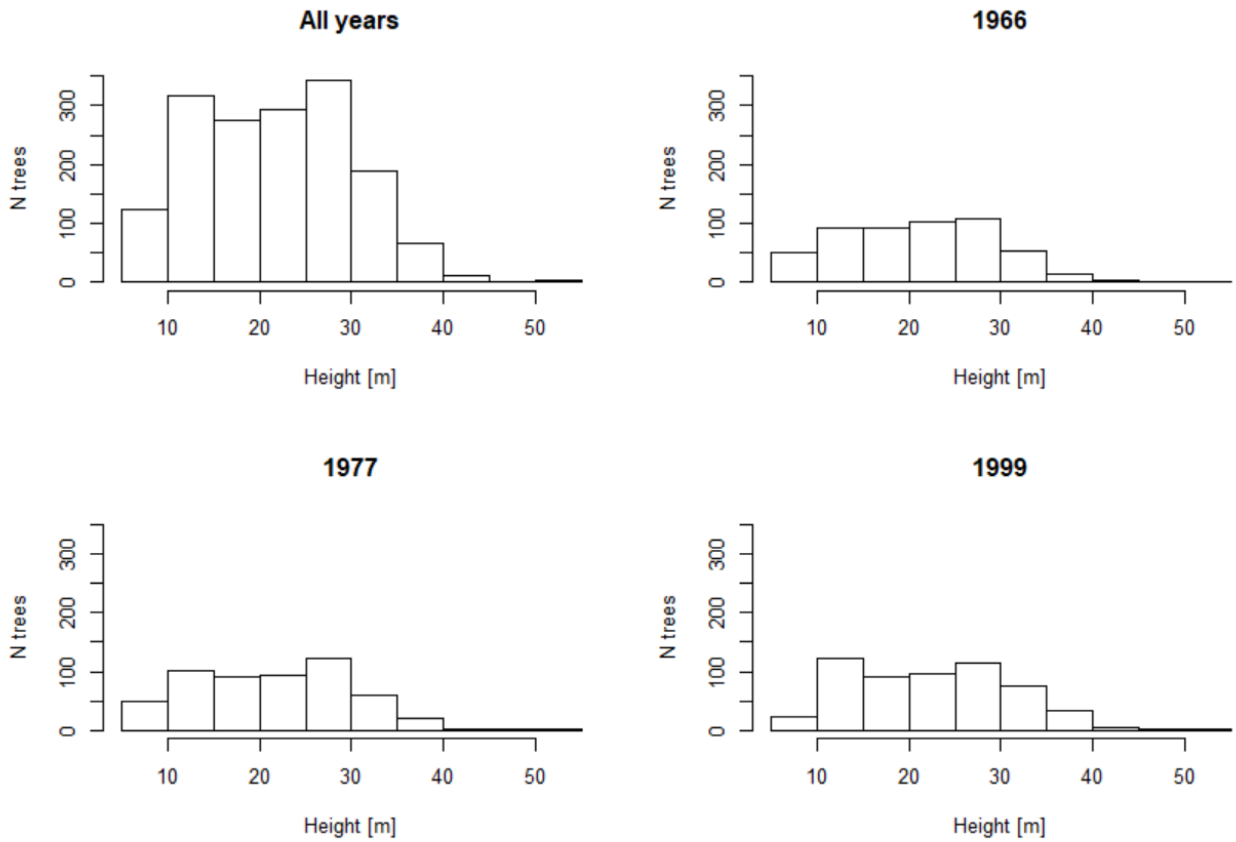

Figure S3. Distribution of reconstructed tree heights across drought years.

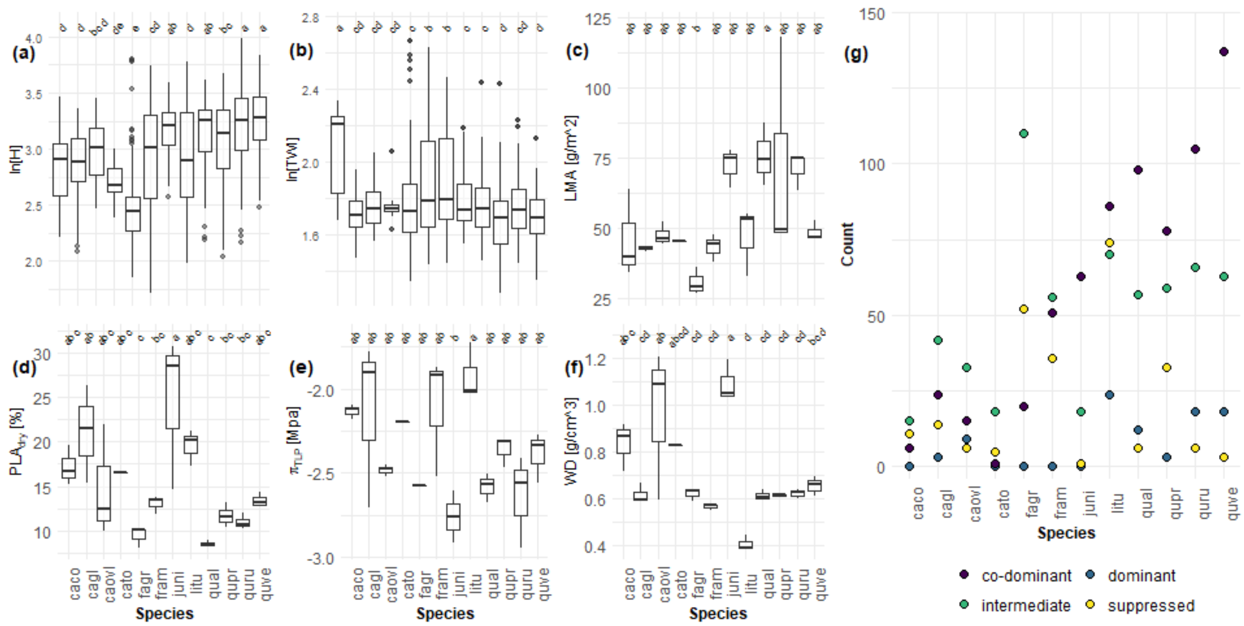

Figure S4. Distribution of independent variables by species. Species that are assigned the same letter are not significantly different from each other with regard to the tested variable. Letter groupings do not transfer between variables.

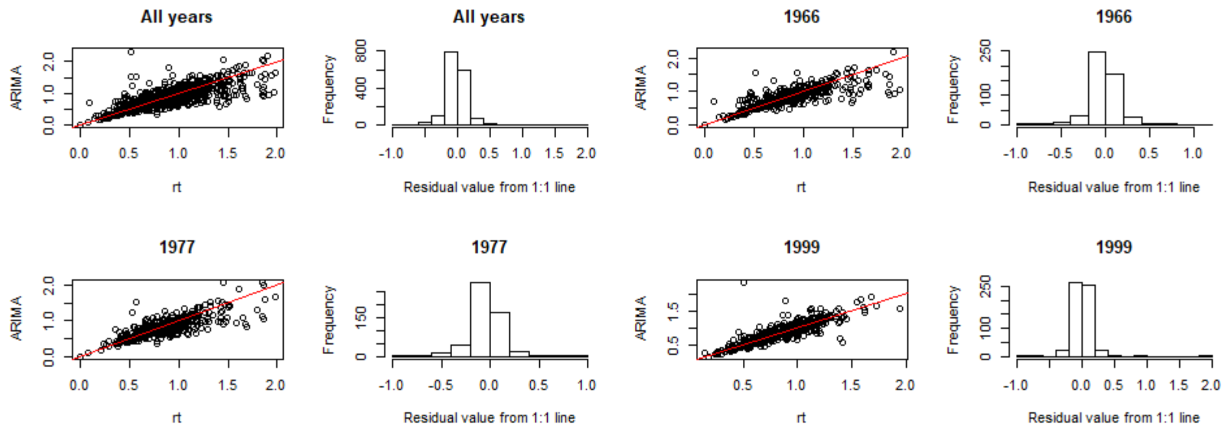

Figure S5. Comparison of Rt and Rt_{ARIMA} results, with residuals, for each drought scenario

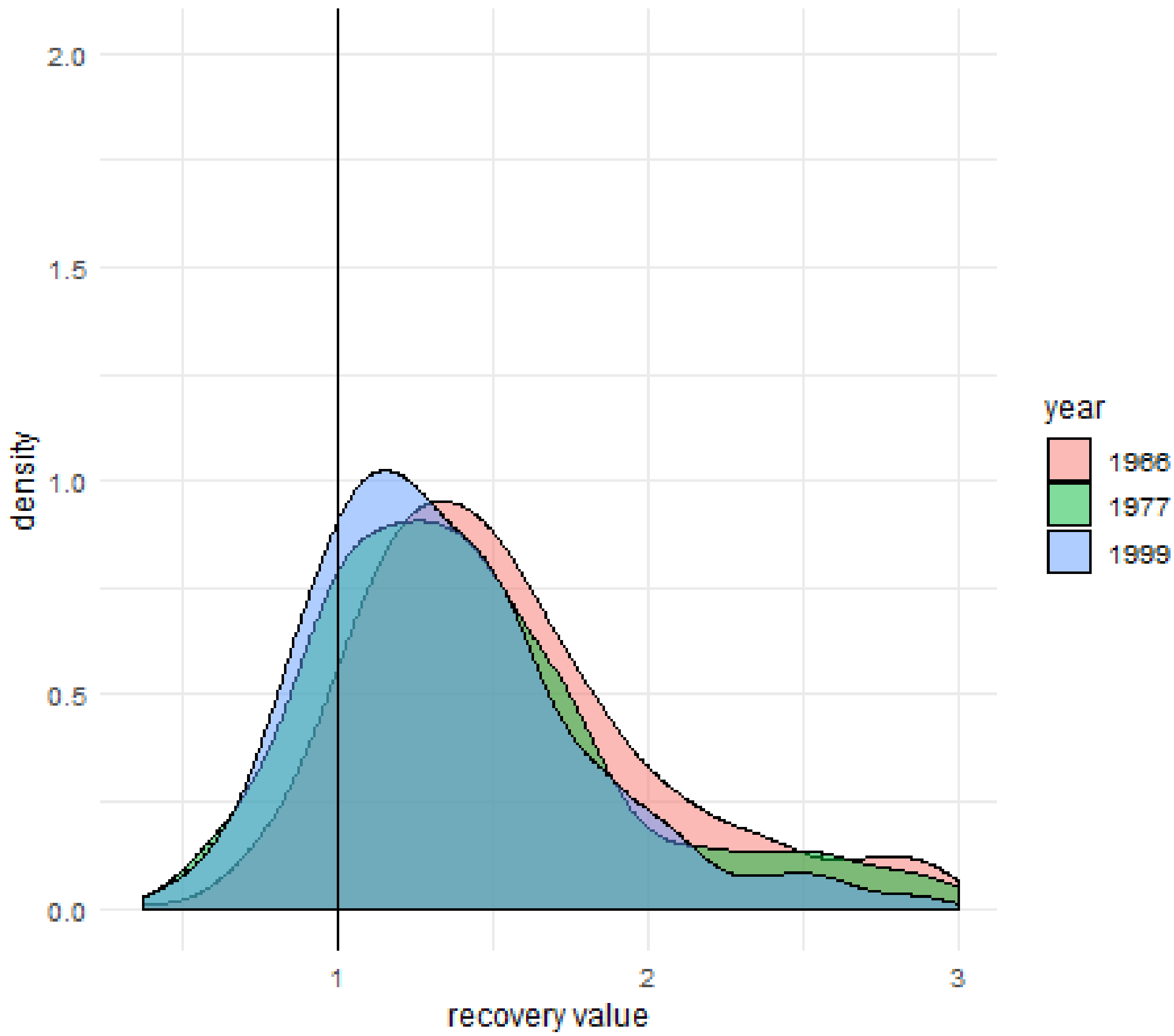

Figure S6. Density plot of Recovery (Rc) values for each focal year.

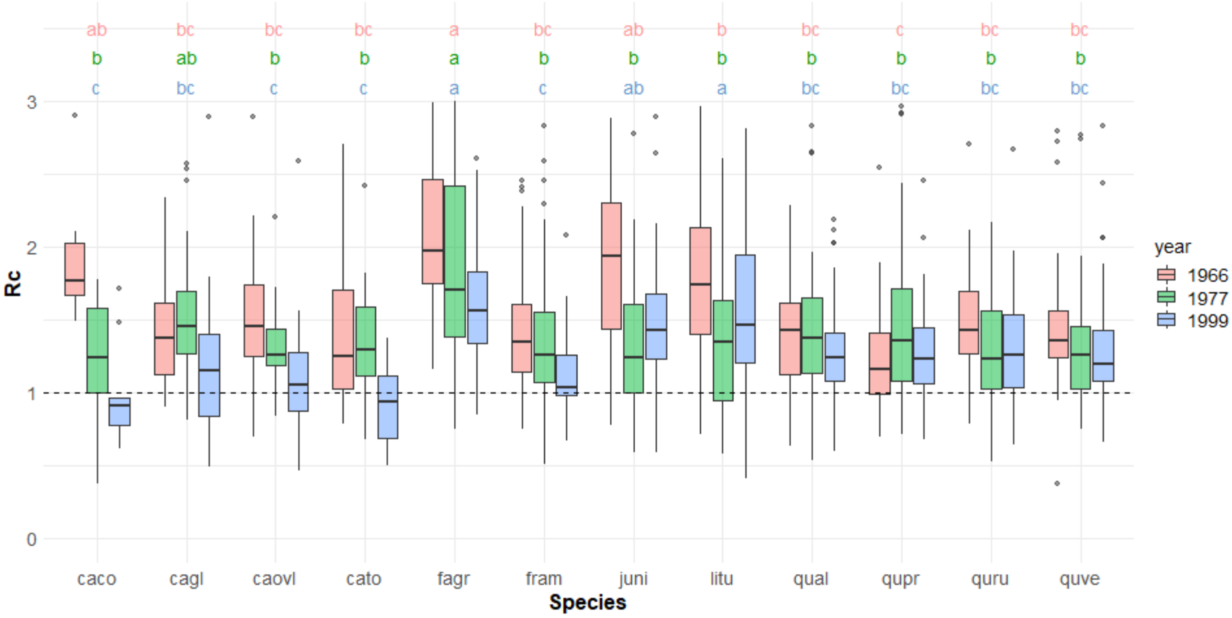

Figure S7. Drought recovery, Rc, across species for the three focal droughts.

Methods S1. Further Package Citations

While there were several R-packages we used for a specific purpose in our methods, numerous packages were immensely helpful for this research behind the scenes. R-packages not already cited in the main manuscript include the following, listed alphabetically by corresponding package name:

R base (R Core Team, 2019); broom (Robinson & Hayes, 2020); car (Fox *et al.*, 2019); cowplot (Wilke, 2019); data.table (Dowle & Srinivasan, 2019); devtools (Wickham *et al.*, 2020b); dplR (Bunn *et al.*, 2019); dplyr (Wickham *et al.*, 2020a); extrafont (Winston Chang, 2014); ggplot2 (Wickham *et al.*, 2019); ggpubr (Kassambara, 2020); ggthemes (Arnold, 2019); gridExtra (Auguie, 2017); knitr (Xie, 2020); lubridate (Spinu *et al.*, 2018); MuMIn (Barton, 2019); piecewiseSEM (Lefcheck *et al.*, 2019); png (Urbanek, 2013); purrr (Henry & Wickham, 2019); raster (Hijmans, 2020); rasterVis (Perpinan Lamigueiro & Hijmans, 2019); RCurl (Temple Lang, 2020); readxl (Wickham & Bryan, 2019); reshape2 (Wickham, 2017); rgdal (Bivand *et al.*, 2019); rgeos (Bivand & Rundel, 2019); rmarkdown (Allaire *et al.*, 2020); sf (Pebesma, 2020); stringi (Gagolewski *et al.*, 2020); stringr (Wickham, 2019); tidyr (Wickham & Henry, 2020)

References

Allaire J, Xie Y, McPherson J, Luraschi J, Ushey K, Atkins A, Wickham H, Cheng J, Chang W, Iannone R. **2020**. *Rmarkdown: Dynamic documents for r.*

Arnold JB. **2019**. *Ggthemes: Extra themes, scales and geoms for 'ggplot2'.*

Auguie B. **2017**. *GridExtra: Miscellaneous functions for "grid" graphics.*

Barton K. **2019**. *MuMIn: Multi-model inference.*

Bivand R, Keitt T, Rowlingson B. **2019**. *Rgdal: Bindings for the 'geospatial' data abstraction library.*

Bivand R, Rundel C. **2019**. *Rgeos: Interface to geometry engine - open source ('geos').*

Bunn A, Korpela M, Biondi F, Campelo F, Mérian P, Qeadan F, Zang C. **2019**. *DplR: Dendrochronology program library in r.*

Dowle M, Srinivasan A. **2019**. *Data.table: Extension of 'data.frame'.*

Fox J, Weisberg S, Price B. **2019**. *Car: Companion to applied regression.*

Gagolewski M, Tartanus B, IBM, Unicode, Inc., Unicode, Inc. **2020**. *Stringi: Character string processing facilities.*

Henry L, Wickham H. **2019**. *Purrr: Functional programming tools.*

Hijmans RJ. **2020**. *Raster: Geographic data analysis and modeling.*

Kassambara A. **2020**. *Ggpubr: 'Ggplot2' based publication ready plots.*

Lefcheck J, Byrnes J, Grace J. **2019**. *PiecewiseSEM: Piecewise structural equation modeling.*

Pebesma E. **2020**. *Sf: Simple features for r.*

Perpinan Lamigueiro O, Hijmans R. **2019**. *RasterVis: Visualization methods for raster data.*

R Core Team. **2019**. *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing.

Robinson D, Hayes A. **2020**. *Broom: Convert statistical analysis objects into tidy tibbles.*

Spinu V, Grolemund G, Wickham H. **2018**. *Lubridate: Make dealing with dates a little easier.*

Temple Lang D. **2020**. *RCurl: General network (http/ftp/...) client interface for r.*

Urbanek S. **2013**. *Png: Read and write png images.*

Wickham H. **2017**. *Reshape2: Flexibly reshape data: A reboot of the reshape package.*

Wickham H. **2019**. *Stringr: Simple, consistent wrappers for common string operations.*

Wickham H, Bryan J. **2019**. *Readxl: Read excel files.*

Wickham H, Chang W, Henry L, Pedersen TL, Takahashi K, Wilke C, Woo K, Yutani H. **2019**. *Ggplot2: Create elegant data visualisations using the grammar of graphics.*

Wickham H, François R, Henry L, Müller K. **2020a**. *Dplyr: A grammar of data manipulation.*

Wickham H, Henry L. **2020**. *Tidyr: Tidy messy data.*

Wickham H, Hester J, Chang W. **2020b**. *Devtools: Tools to make developing r packages easier.*

Wilke CO. **2019**. *Cowplot: Streamlined plot theme and plot annotations for 'ggplot2'.*

Winston Chang. **2014**. *Extrafont: Tools for using fonts.*

Xie Y. **2020**. *Knitr: A general-purpose package for dynamic report generation in r.*